Clean Water for Developing Countries

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Abstract

Availability of safe drinking water, a vital natural resource, is still a distant dream to many around the world, especially in developing countries. Increasing human activity and industrialization have led to a wide range of physical, chemical, and biological pollutants entering water bodies and affecting human lives. Efforts to develop efficient, economical, and technologically sound methods to produce clean water for developing countries have increased worldwide. We focus on solar disinfection, filtration, hybrid filtration methods, treatment of harvested rainwater, herbal water disinfection, and arsenic removal technologies. Simple, yet innovative water treatment devices ranging from use of plant xylem as filters, terafilters, and hand pumps to tippy taps designed indigenously are methods mentioned here. By describing the technical aspects of major water disinfection methods relevant for developing countries on medium to small scales and emphasizing their merits, demerits, economics, and scalability, we highlight the current scenario and pave the way for further research and development and scaling up of these processes.

This review focuses on clean drinking water, especially for rural populations in developing countries. It describes various water disinfection techniques that are not only economically viable and energy efficient but also employ simple methodologies that are effective in reducing the physical, chemical, and biological pollutants found in drinking water to acceptable limits.

INTRODUCTION

What Is Clean Water?

Water for drinking, or potable water, is of paramount importance. The availability of water globally varies widely in different countries, and even if it is available, whether it is clean for human consumption is questionable. This is especially true for developing countries, where access to clean drinking water is limited. The present review explores clean water, especially with respect to drinking water. The technologies available at present, their evolution, and emerging novel technologies are described with a focus on developing countries; we address the medium to small scale, as on the large scale, enough information is available. Moreover, there is no difference in the treatment techniques on a large scale, irrespective of level of development of the country.

Clean water essentially means water that is appropriately free from physical, chemical, and biological pollutants and may be employed for purposes such as drinking, bathing, and cooking. With respect to potable use, clean water means water that is fit for drinking. This implies again that it should be free of all pollutants and must adhere to the guidelines of a suitable water regulatory authority.

The World Health Organization (WHO) in its millennium development goals (MDGs) aims at reducing by half, by the year 2015, the population of people without sustainable access to safe drinking water. According to WHO, safe drinking water is water with microbial, chemical, and physical characteristics that meet WHO guidelines or national standards on drinking water quality (1). The guidelines are described in **Table 1**.

Need for Clean Water

According to the definition laid out in the preceding section, it is imperative that every human being has access to safe drinking water, as it is the right of every individual. The microorganisms that are likely to be found in unclean waters are of myriad varieties of which bacteria, viruses, and protozoa are the broad variants. Among bacteria, *Escherichia coli*, *Vibrio cholera*, *Salmonella typhosa*, and *Shigella flexneri* are some of the common microbes found in water and are responsible for gastroenteritis, cholera, typhoid, and dysentery, respectively. Polio virus and hepatitis virus, which cause muscular paralysis and hepatitis fever, respectively, are the most common viruses encountered in water.

Protozoa that are strongly linked with poor domestic and personal hygienic conditions and unsanitary sewage disposal are *Entamoeba histolytica*, which causes amoebiasis; *Schistosoma mansoni*, associated with schistosomiasis; *Giardia lamblia*, linked to giardiasis; and *Cryptosporidium parvum*,

Table 1a Microbial contaminant limits (1)

S. No	Microbial contaminant	Maximum contaminant level goal (MCLG) in mg/l
1	Heterotrophic plate count (HPC)	n/a
2	Total coliforms including fecal coliforms and *Escherichia coli*	0
3	*Cryptosporidium*	0
4	*Giardia lamblia*	0
5	*Legionella*	0
6	Viruses	0

n/a = turbidity.

Table 1b Chemical contaminant limits (1)

S. No	Chemical contaminant	MCLG in mg/l
Inorganic contaminants		
1	Antimony	0.006
2	Arsenic	0
3	Chromium	0.1
4	Cyanide	0.2
5	Fluoride	4
6	Lead	0
7	Mercury	0.002
8	Nitrate	10
9	Nitrite	1
Organic contaminants		
1	Acrylamide	0
2	Carbon tetrachloride	0
3	Dichloromethane	0
4	Ethylbenzene	0.7
5	Polychlorinated biphenyl	0
6	Vinyl chloride	0
7	Xylenes (total)	10
Radioactive contaminants		
1	Alpha emitters	0
2	Beta/photon emitters	0
3	Combined radium 226/228.	0
4	Uranium	0
Disinfectants		
1	Chloramines	*MRDLG = 4
2	Chlorine	*MRDLG = 4
3	Chlorine dioxide	*MRDLG = 0.8
Disinfectant by-products		
1	Bromate	0
2	Chlorite	0.8
3	Haloacetic acids	n/a
4	Total trihalomethanes	n/a

*MRDLG = Maximum Residual Disinfectant Level Goal; n/a = turbidity.

connected with cryptosporidiosis, to name a few. These and many other microorganisms lead to a range of disease manifestations in humans that can be as simple as mild gastroenteritis or as dangerous as potentially fatal cholera or even dysentery.

Therefore, drinking water should be free from any of these harmful microorganisms. However, waterborne diseases are a major challenge globally. WHO estimates that nearly 1.6 million people die every year from diarrhea, and 90% of these are children younger than five years of age, mostly in developing countries (1). Therefore, controlling pollution on one hand and developing effective disinfection methods on the other are the two most important approaches available to handle the crisis.

Table 2 List of developing countries (93)

S. No	Continent	Region	Countries
1	Africa	North	Algeria, Egypt, Libya, Morocco, Tunisia
		South	Angola, Botswana, Lesotho, Malawi, Mauritius, Mozambique, Namibia, South Africa, Zambia, Zimbabwe
		East	Burundi, Comoros, Democratic Republic of the Congo, Djibouti, Eritrea, Ethiopia, Kenya, Madagascar, Rwanda, Somalia, Sudan, Uganda,United Republic of Tanzania
		West	Benin, Burkina Faso, Cape Verde, Côte d'Ivoire, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone
		Central	Cameroon, Central African Republic, Chad, Congo, Equatorial Guinea, Gabon, Sao Tomem and Principe
2	Asia	East	Brunei, Darussalam, China, Hong Kong SAR, Indonesia, Malaysia, Myanmar, Papua New Guinea, Philippines, Republic of Korea, North Korea, Singapore, Taiwan Province of China, Thailand, Viet Nam
		South	Bangladesh, India, (Islamic Republic of) Iran, Nepal, Pakistan, Sri Lanka
		West	Bahrain, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, Turkey, United Arab Emirates, Yemen
3	Latin America and the Caribbean	Caribbean	Barbados, Cuba, Dominican Republic, Guyana, Haiti, Jamaica, Trinidad and Tobago
		Mexico and Central America	Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama
		South America	Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay, Venezuela

WATER IN DEVELOPING COUNTRIES

In 1990, WHO and UNICEF formed a joint monitoring program (JMP) in water supply and sanitation based on their pooled resources and experiences. The JMP is considered the best source of global data on water and sanitation access in developing countries. The list of developing countries is provided in **Table 2**. The JMP publishes annual reports that encompass the global scenario with respect to water and sanitation availability (2). A major disparity among the urban and rural populations has been recorded, which means that the improvements in terms of water and sanitation have reached the wealthier section of society compared with the rural sections. Therefore, the major focus in the coming years must be on the developing nations and their rural populations.

It is interesting to note the trends in piped water on premises during the period from 1990 to 2012, during which more than twice as many people gained access to piped water on premises compared with any other improved sources. This was significantly reflected in the case of urban populations, although over the past 22 years, some rural populations have also gained access to piped water on premises (**Table 3**). The JMP also describes a drinking water ladder to enable different countries to adopt and understand a uniform standard (**Table 4**). Several experts globally have recommended some very ambitious yet achievable targets for 2030 under the water, sanitation, and hygiene scheme of the United Nations, one of which is universal access to safe drinking water, as it is considered one of the basic human rights.

Table 3 Population gaining access to improved water sources (1990–2012) (2)

S. No	Water Source	Population (millions)	
		Urban	Rural
1	Piped water on premises	1,140	438
2	Other improved sources	277	413

POLLUTANTS

Water may be contaminated by a variety of substances (**Figure 1**) depending on the source of the water body, the environmental factors, and human activity. Physical contaminants lead to turbidity of water owing to the presence of materials like clay, microorganisms, or soil runoff, and particles in water bodies may harbor microbes (pathogenic or nonpathogenic). Microbes enter into water bodies mainly in the form of, e.g., animal and human wastes or runoff from farms.

A spectrum of microorganisms can be found that includes bacteria such as *E. coli*, fecal coliforms, fecal streptococci, *Salmonella*, *Shigella*, *Pseudomonas aerogenosa*, *Campylobacter jejuni*, and *Aeromonas* species; viruses; and microscopic plants called phytoplankton, which cause infections and immunogenic conditions in humans. Protozoa like *Giardia*, which causes giardiasis, and *Cryptosporidium*, which causes crytosporidiasis, are major pathogens. Infections in immunocompromised patients, such as those suffering from AIDS, can be fatal. As a result, the US Environmental Protection Agency (EPA) has set a maximum contamination level goal of 0 for *Cryptosporidium*.

The inorganic contaminant arsenic is one major pollutant that can lead to skin, bladder, kidney, and liver disorders, lung cancer, and hyperkeratosis. Lead poisoning can be fatal, and small levels also can lead to intellectual and neurological defects in infants and young children. It is believed that lead poisoning was the major reason for the fall of the Roman Empire because in ancient Rome, water pipes were made of lead (3). Ingesting antimony-contaminated water can lead to an increase in blood pressure, heart ailments, and ulcers. Fluoride is generally added to drinking water on the recommendation of dental authorities. The EPA states that fluorides in excess of 4 mg/L may lead to bone diseases. This was further reduced to a secondary fluoride standard of 2 mg/L to prevent dental fluorosis, a condition in which the teeth become pigmented. Children below nine years of age are generally at higher risk. Higher doses can also lead to skeletal fluorosis. Nitrates can be a serious problem in the case of bottle-fed infants younger than 3 months of age, as they lead to methemoglobinemia or blue baby syndrome, in which the tissues do not get the required oxygen (4).

Apart from these inorganic contaminants, perchlorate, thallium, chromium, cyanide, and endocrine disruptors, which are chemicals that interfere with the endocrine system by mimicking the body's natural hormones when present in water, are known to cause cancer. Organic contaminants,

Table 4 Drinking water source classification (2)

Unimproved sources	Surface drinking water sources	River, lake, pond, stream, dam
	Unimproved sources	Unprotected dug well, spring, bottled water
Improved sources	Other improved sources	Public taps, tube wells, boreholes, protected springs, rainwater collection
	Piped water on premises	Piped water connections located inside the user's plot or yard

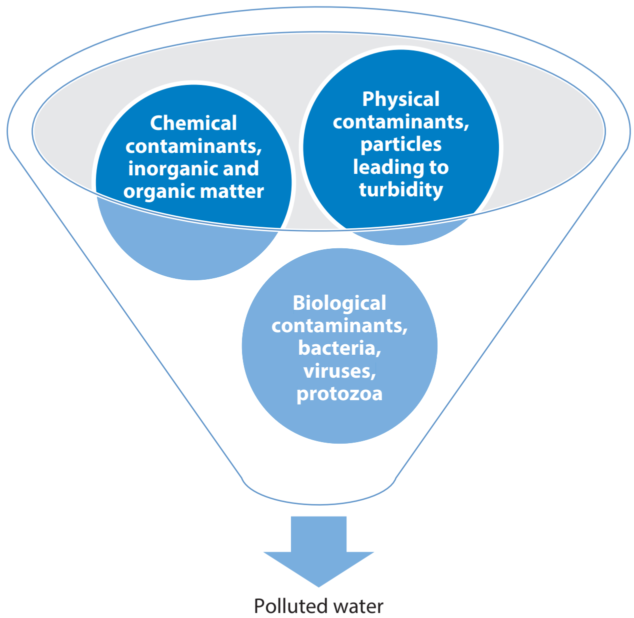

Figure 1

Common physical, chemical, and biological pollutants that contaminate water.

such as pesticides and organotins, a group of organic compounds that contain tin and volatile organic compounds (e.g., trichloroethylene and tetrachloroethylene), are also carcinogenic.

Radioactive contaminants, generally classified as alpha emitters, beta/photon emitters, or combined radium 226/228, radon gas, uraniam, tritium, and thorium, also have carcinogenic properties. Excess disinfectants added during natural calamities or heavy rainstorms to ensure killing of microorganisms can also be lethal.

Disinfection by-products (DBPs) are formed when disinfectants used for water treatment combine with organic matter in water. Trihalomethanes are an important class of DBPs that are potentially carcinogenic, and in the United Kingdom their limits are approximately 100 μg/L. Other adverse effects include liver, kidney, and central nervous system disorders. Haloacetic acid, bromated compounds, and chlorites lead to carcinogenic conditions in humans.

MTBE (methyl-tertiary-butyl ether), used as a fuel additive in the United States to decrease carbon monoxide and restrict ozone depletion caused by auto emissions, can be harmful when present in high concentrations in water (5). Currently, standards for MTBE are being set by the water regulatory authorities. Some of the above contaminants and their maximum limits as per the US EPA are stated in **Table 1*a*,*b***. Jyoti & Pandit (6) have listed the roles of DBPs and their link with the treatment techniques.

DRINKING WATER TREATMENT TECHNIQUES

Solar Disinfection

The use of solar radiations for water disinfection dates back many centuries. This simple yet effective method for water disinfection has tremendous potential for applications in developing countries given its low cost and zero energy requirements. The technique's simplicity is based on the ability of microorganisms present in contaminated water to directly absorb solar rays (near UV A), leading to its inactivation. In addition, sunlight is also known to excite molecules such as pigments and porphyrins present inside the cells, which in turn results in the formation of reactive oxygen species (ROS) like hydrogen peroxide that cause damage to the cell membrane, proteins, and DNA (6, 7). Thermal effects of solar disinfection (SODIS), called solar pasteurization, are also implicated in the disinfection process, during which the absorption of solar infrared rays raises the temperature of water, leading to the inactivation of microbes (8). SODIS involves filling a transparent glass or plastic bottle with the water to be treated and exposing it to sunlight, usually for several hours.

Initial studies on SODIS were reported in the late 1880s when Downes & Blunt (9) initiated the first systematic studies. A plethora of microbes like *E. coli*, fecal coliforms, and pathogenic microorganisms like *Salmonella typhi* and *Shigella flexneri*, several yeasts, and molds can be inactivated by SODIS. Exposing water in bottles or plastic bags to sunlight can effectively disinfect the next day's supply of water after a natural disaster, an easy method that can be adopted by the local population without any special assistance (10).

The most extensive studies of the dynamics of SODIS have been carried out by using bacteria, especially with pure cultures of the fecal indicator bacterium *E. coli*. Typical inactivation curves (**Figure 2**) show an exponential decrease in the bacterial count against time, often with an initial shoulder or plateau lasting 0.5–2 h, corresponding to a delay in the inactivation process. This shoulder is most marked in stationary phase cells (11) and is generally interpreted in terms of a multiple target model of inactivation (12, 13). After this initial shoulder, the inactivation kinetics generally follows a single-exponential decay function, giving a straight line on a log-linear graph (12, 13).

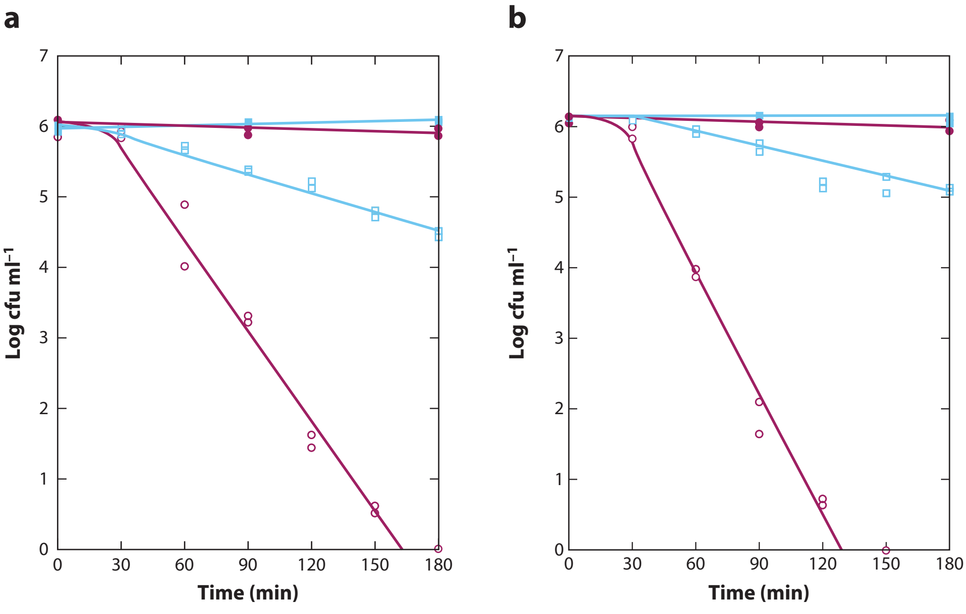

Figure 2

Inactivation of *Escherichia coli* by solar disinfection (11). The lines show the inactivation of (*a*) *Escherichia coli* and (*b*) *Enterococcus faecalis* in the stationary phase, under sunlight aerobically (*open circles*) or anaerobically (*open squares*) or under darkness aerobically (*closed circles*) or anaerobically (*closed squares*).

Table 5 Factors affecting solar disinfection (SODIS) efficiency (14)

S. No.	Factor	Requirement	Effect on SODIS
1	Irradiation time	5 h or 555 Wh/m^2 dose	Minimum requirement under clear sky to inactivate 10^5 *Escherichia coli* in water
2	Container type and material	Transparent PET bottles	This allows UV A rays to penetrate water sample
3	Bottle aging	Cannot be reused multiple times	Loss of light transmittance with extended use
4	Presence of photoproduct precursors	Should be absent	Can lead to by-product formation affecting the quality of water
5	Geographical area	Up to 35 latitude N or S	Maximum irradiation obtained
6	Seasons and weather	Summer and clear weather	Intensity of solar radiation varies with time of the day, date, location, and weather
7	Water quality and depth in bottle	Turbidity <30 UNT and water layer of 0.1 m	Turbidity and increase in depth of water layer makes the penetration of UV rays difficult
8	Bottle modifications	Bottle with lower half painted black	Increases efficiency of SODIS

Wegelin et al. (13) have shown that viruses such as coliphage f2, bovine rotavirus, and encephalomyocarditis virus are inactivated by sunlight. Subsequently, the SODIS Foundation (14) was set up to further investigate the effectiveness of SODIS, and this has led to a spectrum of aspects described in **Table 5**. Although chlorination is the most frequently used disinfection method in rural communities owing to its low cost and easy handling (15), SODIS has very good potential as an alternative; this spurred some research in the 1990s (11, 13, 16–18).

In the late 1990s, researchers added simple dyes, such as methylene blue or rosebengal, to enhance the production of ROS in aqueous solution and thereby increase the antimicrobial effects of light (13, 19). Continuing efforts in the search for effective photosensitizers led researchers to titanium dioxide (TiO_2), which could be used as a stable photosensitizer because excitation of TiO_2 by short-wavelength light (<385 nm) leads to the generation of ROS, principally hydroxyl radicals (20, 21). Thus, conventional batch-process SODIS can be modified to take advantage of TiO_2-enhanced photocatalysis, thereby reducing the irradiation dose (22), reducing the duration of exposure to sunlight, and extending the range of microbes against which it is effective (22). This addition of TiO_2 could also make the process continuous; otherwise, SODIS is essentially a batch process. Salih (23) has also proposed a more complex model based on the combined effects of (*a*) exposure and (*b*) bacterial load.

Interestingly, electric field enhancement on the catalyst surface boosted the production of hydroxyl radicals and thereby the overall effectiveness of the process (23). This technique was called photoelectrocatalytic disinfection (24). Photocatalytic inactivation has also been reported for several other microbes, including bacteria, *Enterobacter cloacae* (25), *E. coli* (26), fungi, *Candida albicans* (27), viruses, polio virus (28), and some protozoa like *C. parvum* (29). Optical effects alone are unlikely to inactivate protozoan cysts, as shown for *Acanthamoeba polyphaga* (27).

In an interesting work on SODIS for water disinfection in a rural community in the state of Chihuahua, Mexico, water quality improved via complete elimination of coliform bacteria, which made the water free of pathogens and fit for human consumption. To augment SODIS, use of half–black painted bottles and solar concentrators was recommended (30).

Eventually, more efforts were directed toward the disinfection of *Cryptosporidium* oocycts, a major waterborne pathogen. The excellent photocatalytic properties of TiO_2 have also been exploited for the regeneration of absorbents such as zeolites, which retain adsorbing properties after several adsorption cycles. This was reported for humic acid removal from water by TiO_2-coated zeolites (31). The inefficiency of SODIS for disinfection purposes can be improved by concentrating the sunlight, i.e., by using a solar collector disinfection system. An approximately 30% to 40% increase in disinfection efficiency compared with use of SODIS alone has been reported (32).

In the past five years, several additives have been used to enhance and accelerate SODIS. These include chemical agents, such as hydrogen peroxide, copper, and ascorbate, as well as natural food preservatives and commonly available ingredients, such as lemon, lime, and vinegar. In one study, 100–1,000 mM of hydrogen peroxide and 0.5% to 1% lemon and lime juice could rapidly enhance SODIS. There appears to be a tremendous scope in accelerating SODIS by using natural ingredients, such as spices commonly found in households. Water boiled with *Cuminum cyminum* (cumin) powder has been used for centuries, especially in the state of Kerala, India. Its positive effects on the digestive and circulatory systems, topped with its antiseptic properties, have been the main reason for its addition to drinking water (33). Camphor (*Cinnamomum camphora*) also has similar benefits when added to drinking water (34). Recently, the emphasis has been to study SODIS on a larger scale. Several examples of SODIS are mentioned in **Table 6**.

Filtration

Filtration employing naturally occurring materials appears to be an economic way to achieve safe drinking water in developing countries. Slow sand filtration is one of the oldest and most effective methods that has been employed for decades. It essentially consists of passing contaminated water through a bed of sand and gravel. Studies reveal that the *schmutzdecke* (a thin biological layer of deposited material on the filter) takes approximately 30 days to form, after which higher rates (90% to 98%) of pollutant removal are achieved. This ripening period of the schmutzdecke varies between 14 to 30 days and depends entirely upon the material of the filter, source water being filtered, levels and types of pollutants, and environmental conditions. A fully formed schmutzdecke may be able to remove more than 97% of *E. coli*, almost 99% of protozoa and helminthes, approximately 50% to 90% of organic or inorganic pollutants, up to 95% of iron, and approximately 90% of arsenic. Some pollutants, such as salt, magnesium, and calcium, cannot be removed by biosand filters. Organic contaminants and complete elimination of pathogens cannot be guaranteed. Therefore, there is always a need for additional disinfectants to be used after biosand filtration to ensure safe microbial levels. Simplicity of design makes biosand filtration an ideal technique for use in developing countries. However, procuring uncontaminated sand and gravel as well as locating suppliers for filter components may take the longest time (35).

Over a period of time, other filter materials have been explored, including ceramic. In an interesting work, effectiveness of point-of-use (POU) ceramic filters was investigated. Water spiked with *E. coli* was passed through six ceramic filters with different utilization histories. Approximately 3–4-log *E. coli* deactivation was obtained, and efficiency dropped by 1 log inactivation on subsequent reuse of filters. Although coating the filters with silver improved the disinfection efficiency, filters could not sustain multiple reuses. Moreover, multiple runs through the filter resulted in sloughing of the bacteria trapped inside the filter, thereby contaminating the water with *E. coli* (36). Further work along similar lines was carried out for assessing the efficiency of removal of virus- to protozoan-sized particles by POU ceramic filters. Water spiked with modified polystyrene particles and natural clays ranging from 0.02 mm to 100 mm in size was

Table 6 Water disinfection using solar disinfection (SODIS)

S. No	Target microorganisms	SODIS conditions	Salient points	Reference
1	*Aspergillus niger*, *Aspergillus flavus*, *Candida* sp. *Geotrichum* sp. *Penicillium* sp.	6–8 h	Inactivated by UV A rays within 3 h	93
2	*Escherichia coli*	6 h	99.9% inactivation with T_{90} of 38	94
3	*Shigella* flexneri	6 h	99.9% inactivation with T_{90} of 67	95
4	*E. coli* K12 (ATCC, 10798)	Immobilized photocatalyst (TiO_2 on plastic sheet inserted in PET bottle)	20–25% increase in efficiency than only SODIS	22
5	Bacteria, fungus and cysts of *Acanthamoeba polyphaga*	8 h at 870 W/m^2 in the 300 nm–10 μm range and 200 W/m^2 in the 300–400 nm UV range	4 log reduction Ineffective against the cysts of *A. polyphaga*	97
6	*Cryptosporidium parvum* oocyst	SODIS reactors fitted with flexible plastic inserts coated with TiO_2 powder (SPCDIS) 8–12 h	Oocyst viability reduced from 98% (±1.3%) to 11.7% (±0.9%) versus that achieved using SODIS, 81.3% (±1.6%) to 36.0% (±1.0%)	98
7	*C. parvum* oocysts	≥600 W/m^2 intensity for 4–12 h Water turbidity: 5 to 300 NTU	Greatest effect on SODIS was the intensity of radiation	99
8	Total coliforms (TC), fecal coliforms (FC), heterotrophic plate count (HPC)	SOCO-DIS (SODIS with solar concentrators) 2.5 ml of 0.25% of lemon and 1.7 ml of 0.17% of vinegar per L to augment SODIS	SODIS enhanced by 40% by SOCO-DIS TC: 30–35 CFU/100 ml from 1,500–2,000 CFU/100 ml, FC: 900–1,850 CFU/100 ml to approximately 20–25 CFU/100 ml HPC:150 CFU/ml from 6,500 CFU/ml	86
9	*Acanthamoeba*, *Naegleria*, *Entamoeba*, and *Giardia*	Simulated SODIS with and without riboflavin (250 μM) 550 W/m^2 for 6 h	Log kills of 2.16, 3.59, 1.92, and 1.96 for the stated organisms, respectively; riboflavin increased inactivation of *Acanthamoeba castellanii* cysts	100
10	Coliforms	Clear or blue-tinted glass or plastic bottle 90 min	99.9% reduction	10
11	Total heterotrophic bacteria, coliforms, and *Pseudomonas aeruginosa*	Reflecting aluminum foils, concentrating lenses and mirrors with SODIS	90% inactivation between 10:00 AM and 1:00 PM No regrowth for 1 week at 25°C	101
12	*E. coli*	25-L borosilicate glass tube fitted with a compound parabolic collector	(<1 CFU/100 ml)	102

passed through ceramic filters. Varying results were obtained in the case of submicrometer-sized particles of 0.02 mm to 0.5 mm as compared with larger-sized particles. Coating the filter with colloidal silver enhanced the removal of 0.02-mm-sized particles but did not contribute significantly in the case of larger particles. The authors emphasized the use of simple surrogates to model filtration-based pathogen removal systems for further optimization of the process (37).

In an attempt to provide safe drinking water to low-income communities in Southern Africa, four different filtration systems were compared for disinfection efficacy. These were the biosand filter, bucket filter, ceramic candle filter, and silver impregnated porous pot filter. Although all the filters exhibited significant chemical and pathogen removal from the source water tested, turbidity was best removed by the ceramic filter, and the silver-coated porous pot filter was found to be the best option for the removal of nitrates and bacteria. The biosand filter gave poor results for microbe removal but was effective for the removal of chemical contaminants. The authors reported that extensive work for further optimization remains to be done to come up with the best option for household drinking water disinfection for developed countries (38).

In an attempt to economize filtration, studies have focused on low-cost materials for ceramic filters. Simonis & Basson (39) developed a microporous ceramic water filter with micrometer-sized pores for elimination of pathogenic bacteria from contaminated source water in a rural area of sub-Saharan Africa. This filter was made using the tradition slip-casting technique involving fewer raw materials and less labor, cost, and energy and could achieve 99.99% bacterial removal efficiency. Apart from bacterial contamination, pesticides in water are also a major concern. In a recent study, Hedegaard et al. (40) investigated the effect of rapid sand filters for treating contaminated groundwater at three Danish waterworks. They found that the filters could effectively remove pesticides such as bentazone, glyphosate, and p-nitrophenol.

Most filters must be cleaned by backwashing to increase their life span. Typically 2,000 to 3,000 L of filtered water or 3 to 6 months of continuous operation is expected of such filters before cleaning or backwashing is needed. Backwashing essentially means reversing and increasing the flow of water passing through the filter to remove the clogged particles from the filter. An increase in clogging results in greater head loss (driving pressure required), which is used as an indicator to begin backwashing of the filter. Turbidity of the filtered water can also be used to indicate when to start backwashing. A rule of thumb of 0.1 nephelometric turbidity units (NTU) is generally employed (41). Self-cleaning filters that are based on upflow filtration and downflow backwashing operation are yet another effective method (42). This is mentioned in the section on rainwater harvesting.

Recycling of used filter cartridges is done in some countries. Brita, an internationally renowned company in the United Kingdom, recycles used filter by cleaning and grinding the plastic body of the cartridge, which is supplied to the plastics industry. The activated carbon (generally used as filter media) is separated from the ion exchangers and returned to the manufacturers, where it is reactivated (regenerated) and reused for operations like waste water treatment. The ion exchanger resin is also purified (regenerated) by chemical processes and reused for production of household water filters (**https://www.brita.co.uk/brita/en-gb/cms/cpd.grid**).

Hybrid Filtration

Owing to the merits of the filtration process, different ways to enhance its efficiency have become one of the many domains of research. One such way is to use different filter materials or to include a disinfection step immediately after filtration to ensure pathogen-free drinking water. Such attempts have been made since the early 1980s, and these techniques may be considered as hybrid filtration. Slow sand filtration followed by storage of the filtered water in a clean copper container to bring about disinfection by copper ions has long been recommended. Specially designed copper plate immersion elements can be used along with earthen containers as cost-effective alternatives in developing countries (43). Indigenously available materials, such as coconut shell, resins, and activated rice husks, along with activated carbon, have been used to adsorb disinfectants like chlorine and iodine, which, when contacted with contaminated water, act as slow-release devices, leading to disinfection (44).

Yet another hybrid filtration unit composed of a candle prefilter, activated carbon filter, and UV irradiation compartment was studied for inactivation of viruses, phages, bacteria, and *Cryptosporidium* oocysts in simulated and naturally contaminated water in South Africa. The unit, named the new-generation Aquaguard POU water treatment unit, could effectively remove all the pathogens tested up to levels of 99.99%, which is well within accepted international norms for POU filters (45).

Apart from these pathogens, presence of *Legionella pneumophila* in water is also a major challenge globally. Hybrid filters have been tested to inactivate these bacteria, and in one such study, metals such as copper and silver were investigated along with POU carbon filters in domestic water systems. Metal-coated filters were found to be more efficient as compared with filters without metals. However, the bacteria was detected even after six weeks of the challenge, indicating that after the initial decrease in the number of bacteria, sloughing from the filters resulted in an increase of bacterial load (46).

Ceramic microfiltration along with activated carbon adsorption, called powdered activated carbon–microfiltration (PAC-MF), is another hybrid filtration technique that has been used to remove organics and viruses from river water contaminated by sewage. Oh et al. (47) recommended the hybrid PAC-MF as a potentially useful advanced water treatment method.

In a further interesting work on the use of metals with filtration, clay pot filters fabricated using terracotta clay and sawdust were used along with copper in the form of a wire mesh for the treatment of surface waters. Among two pore sizes (600 μm and 900 μm) of filters tested, the 600-μm filter completely inactivated *E. coli* and reduced total coliforms by 99.3%. However, the 900-μm filter could reduce *E. coli* by only 99.4% and total coliforms by 98.3%. Presence of the copper mesh with a wire diameter of 0.65 mm in the filter receptacle increased the inactivation rates further and enabled the 600-μm filter to completely eliminate *E. coli* and the 900-μm filter to eliminate it by 99.9% (48).

Additional work on the use of metals in hybrid filtration led to research on silver in the form of nanoparticles as a coating on POU ceramic filter disks. This was compared with a similar disk coated with a polymer-based quaternary amine functionalized silsesquioxane (polytrihydroxysilyl) propyldimethyloctadecyl ammonium chloride (TPA). Studies revealed that TPA was a viable and cheaper alternative to silver nanoparticles, but the possible toxicological effects of its presence in drinking water still must be ascertained (49).

With more and more people using the ceramic pot filters for water purification, extensive work appears to be directed to enhance this simple technology. Use of silver as a hybrid method along with POU ceramic filters has been studied with respect to its role during filtration and subsequent storage. Interestingly, one study (50) revealed that silver coating on the filter did not have a significant impact as compared with the contact with silver in the storage receptacle. This study also emphasized that characteristics of the ceramic filter material did not determine *E. coli* removal efficiencies, but the contact time with silver during storage appeared to be the main factor in the inactivation process (50).

Taking a step further in the hybrid filtration process for developing countries, a combination of coagulation, ozonation, ceramic membrane ultrafiltration, and granulated activated carbon filtration has been proposed for treating micropolluted surface water in southern China. Studies showed that a spectrum of contaminants, such as turbidity (99%), coliforms (100%), dissolved

Figure 3

Terafilter (55). A low-cost household filtration system is composed of a combination of red clay, sand, and wood sawdust produced by microenterprises in Orissa, India. It has noninterconnected pores that prevent clogging of the filter.

organic matter (64%), ammonia (98%), geosmin (96%), and endocrine disrupting compounds (98%), to name a few, were eliminated from the polluted water, thus proving its potential significance for water treatment in developing countries (51).

Recently, polypropylene filters have been modified with metal oxide and reduced graphene oxide by using a hydrothermal process. Positive results indicated that the modified filter holds promise for use in water treatment (52). Water from the Hengjing River in Xinghua, China, was treated with a coagulation-porous ceramic membrane hybrid process, which results showed was effective in eliminating contaminants. The membrane pore size in the range of 20 nm to 500 nm had only a small effect on the water quality of the permeate, and the cake formation on the membrane was found to have a significant influence on water quality. The process has been proposed as a potential technology for surface water treatment (53).

The Terafil water filter (**Figure 3**) is yet another low-cost household filtration system that essentially is composed of a combination of red clay, sand, and wood sawdust that is produced by microenterprises in Orissa, India. Terafil has been reported to remove sediment, suspended particles, dissolved iron, heavy metals, color, odor, and microorganisms from raw water. The unique feature of noninterconnected pores owing to the presence of clay membranes prevents clogging of the filter and is supposedly responsible for its efficiency. During the exhaustive studies carried out by the group, 6-log reduction in *E. coli* and 4-log reduction in various viruses have been reported. The problem of pore blockage owing to the deposition of suspended particles was easily overcome by lightly scraping the surface of the Terafil disc, thus exposing a fresh filtration area. Approximately 10 mm of the Terafil filtration disc thickness was adequate to get the desired level of disinfection of water; thus, the same disc could be used over an expected period with regular scraping without compromising the quality of the disinfected/purified water. The disk can handle flow rates of 2 L/h to 1,500 L/h with a life span of five years for a disc in a single container or multiple discs at the bottom of a storage tank. Its low cost and ability to treat both ground and surface water make it an attractive option for developing countries (54).

Figure 4

Tata Swach® purifier and Tata Swach® Bulb™ with Tata Swach® Fuse™ (107). A low-cost point of use water purifier based on nanosilver. Its replacement cartridge, the Tata Swach® Bulb™, is made of rice husk ash (a waste product of rice mills functionalized with Nano-silver).

Tata Swach® (**Figure 4**) is another low-cost POU water purifier based on nanosilver technology developed through collaborative research by TCS Innovation Labs Tata Research Development and Design Centre and Tata Chemicals Ltd. It was launched in December 2009 at a base price of approximately $21. Its replacement cartridge, the Tata Swach® Bulb™, made of rice husk ash (a waste product of rice mills functionalized with nanosilver), costs only approximately $7 and is designed to treat 3,000 L of water. Interestingly, the purifier also consists of Tata Swach® Fuse™ to stop the flow of water when the bulb reaches the end of its useful life, hence preventing accidental consumption of unsafe water. The purifier has 99.9% microbial removal efficiency, and its recent versions are claimed to remove bacteria, viruses, and cysts, meeting US EPA standards for microbiological water purifiers. Moreover, it does not require electricity or running water for its operation, making it suitable for people residing in villages in India where power and tap water are still scarce (55). The expected running costs of getting disinfected water (after the initial capital investment of about $50 for the filter) work out to be about $12 per 3,000 L of potable water.

Herbal-Based Treatment

Inorganic coagulants are typically used during the water treatment process to remove suspended solids, bacteria, and viruses. Two important chemicals used to aid coagulation in developed countries are aluminum sulphate or alum [$Al_2(SO_4)_3$] and ferric sulphate [$Fe_2(SO_4)_3$]. Considering the cost and health effects of these chemical compounds in water treatment, as they generate a significant amount of iron sludge, a lot of effort has been channeled toward exploring natural alternatives for coagulation-based water purification. This has been very conspicuous in the coagulation process that is carried out to obtain pure drinking water. Among the plethora of natural compounds available, *Moringa oleifera* (drumstick) is particularly noteworthy.

***Moringa oleifera*.** Several coagulants of plant origin have traditionally been used to clean water, e.g., kernels from the genus *Prunus* (almond, apricot, peach) and seeds from the family

Papilionaceae (beans, peas, lentils) (56). Natural plant extracts, such as *M. oleifera*, *Jatropha curcas*, Guar gum, *Strychnos potatorum*, *Hibiscus sabdariffa*, and *Clidemia angustifolia*, have been employed for water purification for several centuries. Among these, *M. oleifera* seeds have been ranked as one of the best plant extracts for water purification (57). The active component of *M. oleifera* causing coagulation is a soluble protein that acts as a natural cationic polyelectrolyte during treatment and causes coagulation in turbid water (58, 59). *M. oleifera* seeds are being recognized as a substitute for wastewater treatment owing to their effectiveness as a water purifier, the multipurpose use of the *M. oleifera* tree, and the fact that the tree is widespread in the tropical belt (60). Treatment of water with *M. oleifera* extracts can achieve 1- to 4-log-unit reduction of pathogens, including fecal bacteria and *S. mansoni* cercariae (61, 62). A surface water study conducted in Ghana for domestic consumption purposes showed a 90.99% reduction in fecal coliform levels after treatment with *M. oleifera* (63). Studies have also shown that *M. oleifera* seeds are effective in reducing the number of helminth eggs by 94% to 99.5% and turbidity by 85.96% in different irrigation water types (64).

The *M. oleifera* tree can produce approximately 2,000 seeds per year, enough to treat about 6,000 L of water using a 50 mg/L dose. Initial studies have focused on using *M. oleifera* as a cocoagulant together with alum. Jahn (65) showed turbidity levels of raw water to be reduced beyond the levels found when alum was used alone. Also, Sutherland et al. (66) used *M. oleifera* and alum together by dosing 15 mg/L alum with 25 mg/L *M. oleifera*. This dose achieved a turbidity removal from 150 NTU to approximately 10 NTU (66).

In a separate study, *M. oleifera* was used separately and compared with common coagulants such as ferric and alum. Even though *M. oleifera* was not found to be as effective as alum and ferric, its use along with sand filtration yielded good results for drinking water, which is especially useful for developing countries as its use relies on locally and naturally available plant products (67). Optimization studies for *M. oleifera* in drinking water purification in developing countries such as Malawi have revealed that the most suitable dosing method was to mix the powder into a concentrated paste, hence forming a stock suspension. The optimum *M. oleifera* dose for turbidity values between 40 NTU and 200 NTU ranged between 30 mg/L and 55 mg/L. The process was not substantially affected by pH fluctuations, best results were obtained at pH 6.5 at higher temperatures, and seed age of two years showed a decline in its efficiency (68). Both shelled and nonshelled dry *M. oleifera* seeds can be used as a coagulant, but shelled seeds reportedly were more effective. Moreover, treatment with *M. oleifera* seeds did not significantly affect the quality of the treated water. However, concentration of organic matter in the treated water increased considerably with the dosage of *Moringa* solution. Because this organic matter might exert a chlorine demand and may also act as a precursor of trihalomethanes during disinfection with chlorine, *M. oleifera* seeds may be used as a coagulant in water and wastewater treatment only after an adequate purification of the active proteins (68). *Moringa* seeds with Sudanese bentonite clays have been used to treat Nile water in Sudanese villages. More than 90% reduction in *S. mansoni* was achieved, thus proving it to be a useful alternative method for obtaining water with less risk of spreading schistosomiasis (61).

Recently, the increased use of natural compounds, especially in developing countries such as Malawi, has raised the issue of their toxic effects on humans. Studies have revealed the cytotoxicity and genotoxicity of powdered *M. oleifera* seeds in the concentration from 1 mg/L to 50 mg/L (routinely used for coagulation). Based on cytoxicity and genotoxicity models, the lethal concentration to kill 50% of treated specimen (LC50) and LC90 of *M. oleifera* seeds were found to be 8.5 mg/L and 300 mg/L, respectively, and their genotoxicity was found to be equivalent to 8.3 mg of mitomycin C per 1.0 g of dry *M. oleifera* seed. This was ascertained by using a whole-cell bioreporter as a tool for toxicity assessment (69).

Other natural herbs. India has a tradition of using herbs and natural alternatives for water treatment. Particular use of natural herbs for disinfection of drinking water in rural areas has been reported over the past few years. In one such investigation by Bhattacharjee et al. (62), *Ocimum sanctum* (Tulsi) and *Azadirachta indica* (Neem), herbal plants with antimicrobial activity against many microorganisms commonly found in water sources, were evaluated for disinfection efficiency of lake, river, and well water. In vitro antibacterial studies were carried out using aqueous leaf extract, fresh leaf juice, and alcoholic extract against *S. typhi*, an indicator microorganism. The highest efficiency was observed for alcoholic extract. The authors further suggested the synergistic use of solar rays with natural herbs for rural areas in developing countries (70).

The Department of Science & Technology of the Government of India also suggests in its Water Technology Initiative that use of natural materials to clarify turbid water with seed materials has been found to be effective. By the end of 2007, research was reported on the design of a 10-L turbid water treatment unit for surface water with various levels of turbidity. Agro-based seeds like *M. oleifera* (drumstick), *S. potatorum* (nirmali), *Zea mays* (maize), *Coccinia grandis* (dondakaya), *Abelmoschus esculentus* (ladies' finger), *Pisum sativum* (peas), and *Phaseolus vulgaris* (beans) were nontoxic and effective coagulant aids useful for removing turbidity and bacteria from water. Given the negligible cost of SODIS, it can be combined with seed treatment, which in turn is also very cheap. These methods are very attractive at the household as well at the community level for developing countries. The low volume of precipitated sludge was found to be biodegradable and hence environmentally harmless (71).

Among various herbs, tulsi leaf extract has great potential as an antimicrobial agent for the treatment of water. The components present in *O. sanctum* leaves have no significant side effects to humans compared with chemical treatment. Moreover, the water treated with tulsi extract is not only germfree but also medicinal. This was ascertained in an interesting work reported by Sundaramurthi et al. (72), which focused on the evaluation of antimicrobial activity of *O. sanctum* leaf extract (100–600 mg/L) in normal tap and river water. They observed that 600 mg/L concentration of plant extract–treated water showed effective antimicrobial activity of approximately 95% to 98% at 15 to 16 h compared with the other concentrations of the extract. The minimum bacterial concentration was reported at dosage levels of 500 mg/L and 600 mg/L (72).

In another study, the antimicrobial activity of aqueous and alcoholic leaf extract of *O. sanctum* was investigated, and reduction of approximately 68.75% and 85% microbial load with aqueous and alcoholic leaf extract, respectively, was obtained. Subsequent phytochemical screening of the aqueous leaf extract revealed the presence of alkaloids, steroids, and tannins, and alcoholic leaf extract showed the presence of alkaloids and steroids (73). Further work along similar lines has led to the formulation of a kinetic model to predict water disinfection by natural herbs such as anjan (*Hardwickia binata*), mutha (*Cyperus rotundus*), ushir (*Andropogon muricatus*), and rajkashtaka (*Luffa cylindrica*).

These herbs were tested by the disc diffusion method (Kirby-Bauer method) after extracting the dried material powder in 50% ethanol. Among all the herbs tested, maximum antibacterial activity was observed in anjan. All the herbs tested at 1% concentration resulted in maximum elimination of *E. coli* after 30 min of contact time. The maximum percentage removal of *E. coli* was 82.05%, 48.72%, 41.03%, and 41.03% using anjan, mutha, rajkashtaka, and ushir herb extracts, respectively. Kinetic modeling studies for assessing the performance of the natural disinfectants were conducted. The Chick-Watson model obtained for anjan [$\text{Log}(N/N_o) = -0.17Ct$] was comparable to that of chlorine, which is an established chemical disinfectant (74).

The fate of the herbal disinfectants added after the removal of the sludge has not been discussed anywhere. Because these are of biological origin, they are expected to be completely biodegradable and hence will not pose any environmental hazards. The residual herbal disinfectans remaining in the treated water are in fact known to be nutraceuticals, and no additional bodily harm is expected with the consumption of this treated water.

COMPARATIVE STUDIES ON WATER DISINFECTION TECHNIQUES

In an interesting study (75), three methods of water disinfection, namely boiling, SODIS, and granulated activated carbon, were compared in terms of cost effectiveness, especially for use in developing countries. The investigation entailed analysis of Aso River water samples and a borehole in Nsukka, Nigeria. The authors analyzed the samples for coliforms and total viable count. Results indicated that boiling was very effective in completely eliminating coliforms, and SODIS, although a cheaper alternative, did not bring down the microbial load completely. Ibeto et al. (75) do not recommend the use of granular activated carbon, as it was found to increase the microbial load. This was attributed to the fact that the bed of carbon trapped the bacteria and turned into a breeding ground for microbes, which as a result of sloughing were released into the water being treated (75).

One of the major challenges faced by developing countries is rapid urbanization, which in turn increases the demand for clean water. The literature reports work in Togo, a sub-Saharan country on the west coast of Africa, where a survey was conducted to characterize the existing water supply systems, which consisted of bucket-drawn water wells, miniature water tower systems, rainwater harvesting, and public piped water. Based on the survey, Ahiablame et al. (76) found that the participants preferred a large-scale community water tower to meet their water demands and were also ready to maintain it. The authors recommend this model as the best community water distribution system and further assert the need for research along the same lines to predict models in similar communities of the developing world (76). A huge amount of energy is often required for water treatment and supply globally, and this can be a major hurdle when a water treatment strategy is planned for rural populations, especially in developing countries. Therefore, energy-efficient methodologies must be explored and researched extensively to address these concerns. Although some work has been targeted toward this (77), there still exists ample scope for further investigations.

Yet another aspect of this is to have a financially sustainable business model; there are a plethora of water treatment technologies available, but providing them in a financially sustainable manner, especially to low-income groups, appears to be a major bottleneck. Gebauer & Saul (78) have addressed this. The authors describe four business models in the context of treating water contaminated by fluoride and arsenic—low-value devices for people living in extreme poverty, high-value devices sold to low-income customers, communities as beneficiaries of microwater treatment plants, and entrepreneurs as franchisees for selling water services—and highlight the emergence of hybrid business models. Moreover, cost transparency, cost reductions, business diversification, distribution channels, skills, and competencies are an important part of capacity building for creating even more business model innovations. They conclude that these contributions will create more awareness of the role of business models in scaling up water treatment technologies in the future (78, 79).

Newer pathogens and emerging issues with water contaminated with protozoan cysts are becoming a global concern. Among these, *Cryptosporidium* and *Giardia* oocysts are difficult to mitigate with conventional techniques like coagulation, sedimentation, filtration, and chlorine disinfection. It was observed during several pilot plant-scale and large-scale water treatment studies that protozoan cyst removal was largely influenced by coagulation pretreatment methods, including micro- and nanofiltration and clarification techniques. An effective disinfection method is also of paramount importance to completely eliminate protozoan cysts. In the United States and Europe, the emphasis appears to be on the use of microfiltration and ultrafiltration as compared with the use of UV. The authors recommend and speculate on the use of a multibarrier approach consisting of a combination of filtration and chemical disinfectants to remove microbial contamination as the method of choice (80).

RAINWATER HARVESTING

Rainwater harvesting is used for collecting and storing rainwater from rooftops, land surfaces, runoffs, and catchments. The water becomes a household source for domestic uses, such as drinking and cooking, as well as for use in agriculture. In lowly polluted areas, catchment surfaces and metallic rooftops could be a source of pollutants such as inorganics and heavy metals, at least in the initial monsoon/rainy period. In addition, bacteria, viruses, and protozoans may gain access to the storage areas by way of fecal pollution resulting from birds and mammals. High levels of bacteria, such as 80.3% coliforms, 40.9% *E. coli*, and 28.8% enterococci, have been reported in harvested rainwater, thereby highlighting the necessity to disinfect harvested rainwater prior to its consumption (81).

Disinfection of harvested rainwater has been achieved by several methods, such as chlorination after its removal from the tank to minimize side reactions with inorganic matter settled at the tank bottom. Slow sand filtration and SODIS are particularly useful to eliminate microbial contamination. For particulate matter, rapid sand filtration is one option, and metal membrane filters with ozonation and aeration on the feed side also serve well to remove most of the pathogens and clarify rainwater to an acceptable quality.

Among the various factors influencing the quality of harvested rainwater, rooftop material appears to be of significance, as found during the comparison of different roofing materials in a Korean study (82). Four pilot-scale structures with different roofing materials, such as wood, clay, concrete tiles, and galvanized steel, were studied, and the latter was found to be most suitable for collecting rainwater that met the Korean water quality standards. This was attributed to the effect of UV rays and high temperature, which resulted in significant disinfection (82).

Yet another study highlighting the significance of roofing material in the design of rainwater catchments compared conventional and alternative roofing materials for their effect on the quality of harvested rainwater. The conventional roofing materials consisted of asphalt, fiberglass shingle, metal, and concrete tiles, and the alternative roofing materials included an acrylic-surfaced, two-ply atactic polypropylene–modified bituminous membrane cool roof (basically made of reflective material called cool roof) and an unfertilized (type E) green roof (basically vegetated roof referred to in this study as green roof). Rainwater harvested on these roofing materials had to undergo further disinfection as per US EPA norms. Metal, concrete tiles, and cool roofs could reduce the fecal coliforms significantly, and the shingle and green roof, apart from yielding similar results, also produced higher amounts of dissolved organic carbon, the presence of which could lead to higher levels of disinfection by-products after chlorination. Moreover, higher levels of arsenic in the green roof clearly pointed out the implications of selecting an appropriate roofing material (83).

A decentralized system of treating harvested rainwater by filtration/adsorption disinfection design has been proposed for developing countries. The innovative system consisted of a compact unit combining a filtration process along with an adsorption step on granulated activated carbon and a UV disinfection phase. Results indicated that the unit could be a viable and economic option for developing countries as it can treat most of the chemical and biological pollutants, including turbidity (84).

Microbial contamination of harvested rainwater occurs owing to catchment contact, thereby rendering it nonpotable. Findings by researchers from Seoul National University, Seoul, South

Korea, suggest that silver disinfection, especially in the concentration range of 0.08 mg/L of silver or higher under safe limits, can eliminate *Pseudomonas aeruginosa* and *E. coli*, two test organisms studied. Lower concentrations reportedly could result in the regrowth of these microorganisms (85).

A simple and effective rainwater treatment in buildings was developed based on a novel concept consisting of an up-flow filtration with down-flow backwashing operation. The system could effectively remove particulate matter and exhibited very good backwashing efficiency for self-cleaning and easy maintenance (42). Although simple techniques such as SODIS and SOCODIS (SODIS along with solar concentrators) have been employed for treating stored rainwater, the efficiency of these systems was further enhanced by reduction of pH by way of natural materials, such as lemon and vinegar, that are cheap and locally available. An optimum concentration of 2.5 mL (0.25%) lemon and 1.7 mL (0.17%) vinegar per liter of water has been recommended (86). As most of the water supplied to the Indian urban population is harvested and stored rainwater collected over the four-month monsoon period, this does require the same type of treatment, albeit to a lesser extent, because it is stored in open lakes and is subjected to the same environmental exposure as that of any natural water body.

EMERGING RECENT EFFORTS

Plant Xylem for Water Filtration

Plant xylem—a porous material that is known to conduct fluids in plants—has been studied as a filter medium to provide clean water. In a pioneering work by Boutilier et al. (87), POU filtration devices were prepared from the plant xylem from the sapwood of coniferous trees. The idea was to use the minute pores present in the xylem tissues, which range from a few to 500 nm in size depending upon the plant species (mostly coniferous trees), as a filter. The study revealed that flow rates of approximately 4 L/day could be obtained through a 1-cm^2 filter area at applied pressure of 5 psi. The filter was able to eliminate 99.9% bacteria and is recommended as being sufficient to provide safe drinking water for one person. This meaningful finding reveals the potential of using nature's bounty in the form of plant xylem to address the needs of developing countries with limited resources (87).

Technologies for Arsenic Removal

Arsenic, a metalloid and oxyanion, is found in nature and travels in the atmosphere through natural processes like weathering reactions, biological activity, and volcanic eruptions as well as through human activities. It is known to be toxic, and arsenic poisoning is caused by higher levels of arsenic accumulation in the human body. Apart from affecting the cardiovascular system, kidneys, skin, and nervous system, it is carcinogenic (88). Owing to its carcinogenic nature, WHO has reduced its maximum contamination level from 50 ppb to 10 ppb (μg/L) (88).

It is indeed alarming to note that arsenic pollution is a global concern, and many parts of India, Nepal, and Bangladesh experience more than 50 ppb of arsenic in water bodies. The world's highest contamination level of arsenic is found in Bangladesh and West Bengal, India. Most remediation methods for arsenic removal can effectively remove arsenic from water containing high initial arsenic concentrations (usually >100 mg/L), but residual arsenic concentrations exceed the 0.05 mg/L level required for water quality standards specified in most countries. A plethora of arsenic removal techniques exist, some of which are described in **Figures 5** and **6**.

A pioneering work on electrochemical arsenic remediation (ECAR) was carried out by Dr. Ashok Gadgil from the University of California, Berkeley, and Lawrence Berkeley National

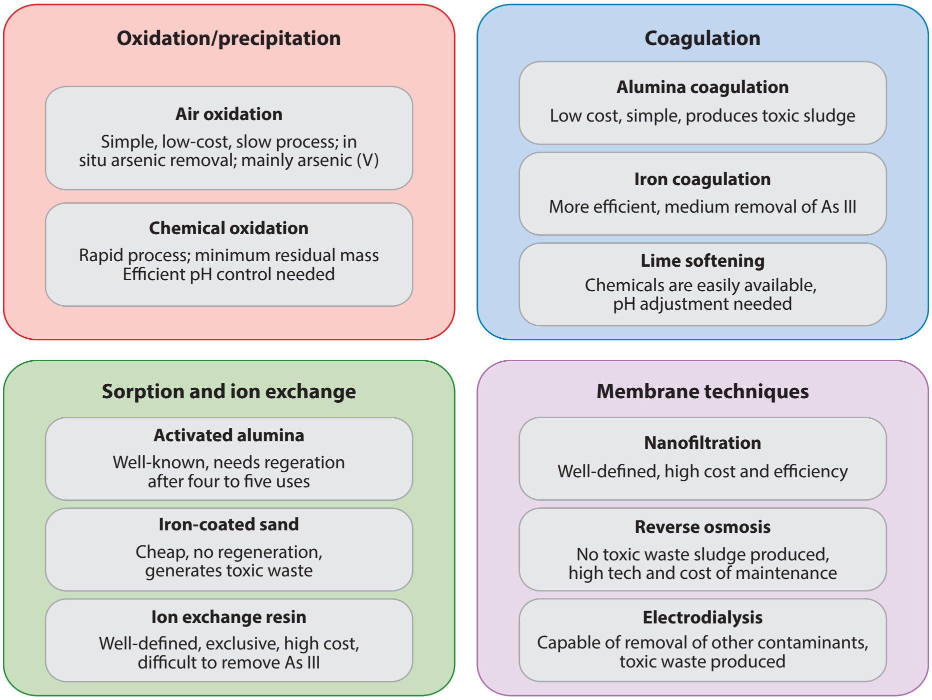

Figure 5

Arsenic removal technologies (106). The figure shows different arsenic removal methods based on oxidation/precipitation, coagulation, sorption, ion exchange, and membrane techniques with the salient features.

Laboratory. The technique involved the use of an electrochemical cell consisting of an iron anode and copper cathode. The Fe-II dissolves and becomes precipitated as Fe-III oxides (rust), turning into a very good sorbent material for arsenic, which can be successfully removed from water (solution). After confirmation by preliminary experiments on synthetic lab water containing arsenic, groundwater from Bangladesh and Cambodia was tested with said technique, yielding a less-than-0.5-ppb arsenic level in water, which was well below the WHO maximum contaminant level. Moreover, it was locally affordable at less than $1/m^3, with no regeneration, no hazardous material formation, a simple supply chain consisting of ordinary steel plate and non-ferric alum, and minimal sludge generation of less than 205 gm/m^3 of treated water. The ECAR was found to consistently deliver water containing less than 5 ppb of arsenic in field trials, and a possible scale-up of community-level arsenic removal systems in an affordable and financially viable way is foreseen. UV Waterworks, which aimed to affordably disinfect potable water in rural communities in developing countries, was yet another meaningful and impactful work of the same group in which a huge population could be served pure drinking water and nearly 1,000 diarrheal deaths could be avoided annually (79).

Innovative Biosand Filters and Tippy Taps

An interesting work carried out in Biome Environmental Solutions by a group of interns under the Wipro Earthian Program clearly describes novel yet simple steps that can be taken to provide clean water to developing countries. A simple biosand filter was constructed using cheap and easily

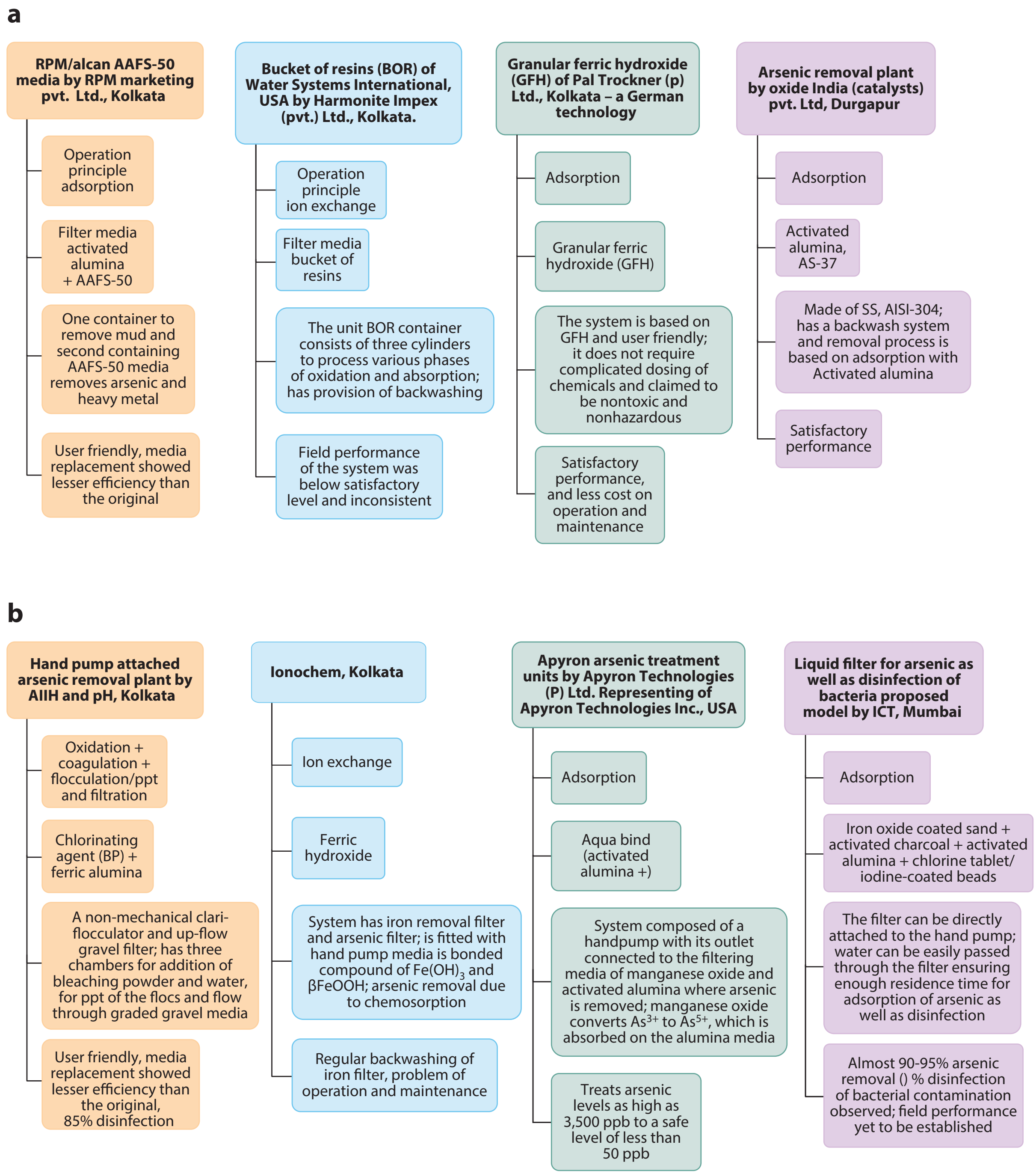

Figure 6

Commercially available products/technologies for arsenic removal (107). (*a*) Types of technologies offered by various companies are described on the basis of the operating principle, methodology, merits, and demerits. (*b*) Types of technologies offered by various companies are described on the basis of the operating principle, methodology, merits, and demerits.

Figure 7

Tippy tap (89). The figure shows a tippy tap prepared by drilling a hole into a plastic can and attaching a simple rope. This is hung onto a tree, and a wooden foot pedal is made and attached to the container cap. This is a hands-free way to wash hands, suitable in rural areas that lack running water.

available resources that consisted of a 20-L plastic barrel, into which previously washed and dried gravel and sand (obtained locally) was added in layers, followed by a topmost layer of activated charcoal. Excellent filtration efficiency (500 mL/min) was reported.

Further innovations to improve biosand filtration, like scraping a small portion of the biolayer, detecting the predominant bacteria present in it, followed by the inoculation of the scraped biolayer into a freshly designed biosand filter, is expected to augment the development of the active biolayer and thereby improve the efficiency of filtration. Construction of tippy taps was another simple but significant endeavor by the group. The tippy tap is a hands-free way to wash hands, appropriate for rural areas where there is no running water, and especially appealing to children. It is operated by a foot lever and thus reduces the chance for bacteria transmission, as the user touches only the soap. Moreover, it uses only 40 ml of water versus 500 ml using a mug. Additionally, the used wastewater goes to plants or back into the water table (**Figure 7**).

According to the global facts and figures about hand washing released by UNICEF in 2010, more than 1.5 million children younger than five years of age die each year as a result of diarrhea, and it is the second most common cause of child deaths worldwide. Hand washing with soap can reduce diarrhea rates by more than 40% and can reduce the incidence of acute respiratory infections by approximately 23%. In their work, the group prepared the tippy tap by drilling a hole into a plastic can and attaching a simple rope. This was hung onto a tree, and a wooden foot pedal was made and attached to the container cap (89).

Table 7 Characteristics of valve (M. Badve & A.B. Pandit, unpublished data)

Geometry	Head Diameter, m	Lift, m	% flow area opening
1	0.048	0.012	100
2	0.048	0.0084	70
3	0.048	0.0048	40
4	0.048	0.0012	10

Table 8 Comparison of water treatment techniques discussed in the review

Type of treatment	Pollutant treated	Scale of operation studied	Capital and running costs	Recommendation
Tata Swach (55)	Turbidity, bacteria, viruses, and cysts	3–4 L/h	Capital cost = $50 Running cost = $4	For household purposes where electricity is not available; mainly useful to eliminate microbes and turbidity
Electrochemical arsenic remediation (79)	Arsenic removal	600 L	Capital cost = 1 US cent/L Operating cost = $0.22/m^3$	For arsenic-polluted water at a community level
Terafil (54)	Turbidity, iron, total coliforms	2–1,500 L/h	<US$0.5 (filter) <US$4.00 (unit)	For household purposes where electricity is not available; useful when water is polluted with bacteria and iron and has high turbidity
Ceramic filters (**http://www.merid.org/nano/watertechpaper**)	Bacteria, coliforms, fecal coliforms, cysts, iron	1–11 L/h	$3.50 (unit) $0.49–$1.02 (filter)	For household use with easy maintenance; useful to treat bacteria and remove iron
Tippy Taps (89)	—	10 L	<$1.5	For handwashing in rural areas lacking running water
SODIS (**http://akvopedia.org/wiki/UV_treatment_/_Solar_disinfection_(SODIS)**)	Bacteria, viruses, protozoa	1–25 L	Capital costs = $0–$5 (PET bottles may be free or cost less than $0.5) Operating cost = $0	For areas with high intensity of sunlight; mainly for household-to-community level; cannot be used for highly turbid waters; eliminates microbial pollutants
Herbal-based treatment (*Moringa oleifera*)	Turbidity, bacteria, helminth eggs, protozoa	1–20 L	Cost of producing 1 kg moringa seeds = $2 (103) and 3 kg needed for treating 30,000 L of water (104)	Very good option for highly turbid waters with microbial contamination at the household level; suitable for areas growing *M. oleifera* (this avoids transportation costs)
Neeri-jar-portable instant water filter (based on sand filtration) (**http://www.indiawaterportal.org/sites/indiawaterportal.org/files/Water%20Technologies_NEERI_2010.pdf**)	Turbidity and microorganisms	18–20 L/h	$40.710 (unit) operating cost = $0.049/1,000 L	For household use to eliminate turbidity and microbial pollutants

Disinfection of Potable Water Using Hand Pumps

Recurrent droughts in India since the mid-1960s made the government conscious of the vital need to provide the rural population with an adequate and safe water supply, especially in the large number of villages dotting the peninsular part of India. With this in mind, the Government of India and various agencies operating on the rural scene have subscribed to the miracle combination of borehole/hand pump as a source of drinking water to a large number of no-source situations in the country. Badve & Pandit conducted a study to provide disinfected water delivered by a standard/modified hand pump (M. Badve & A.B. Pandit, unpublished data). This was based on previous work that indicated that hydrodynamic cavitation was an energy-efficient and economic method for treating of bore well water (90). The hand pump essentially is a positive displacement pump, using negative pressure to lift water from the well to the surface level.

Hydrodynamic cavitation is a common phenomenon at the suction valve in hand pumps, and the collapse pressure generated by the cavity can be of the order of several hundreds of bars (91), which is sufficiently high to rupture the biological constituents of water, including the microbial cells causing its destruction (92). Jyoti & Pandit (90) have suggested that such a situation at the suction valve can be effectively used and possibly optimized or intensified for water disinfection while pumping the water through the system. Computational fluid dynamics simulation, when solved with cavity dynamics models, predicted that maximum collapse pressure of cavities was obtained with 20% flow area opening of the check valve for an initial cavity diameter of 150 μm and 200 μm.

A number of valves with different lifts and head diameters were fabricated to study their effect on microbial cell disruption at various inlet velocities. Initial studies showed that the value of rate constant k increases with an increase in the inlet velocity. The rate constants obtained at inlet velocity of 1.4 m/s and 3.1 m/s were 0.008/s and 0.01/s, respectively. This indicated that as the inlet velocity increases, the rate of disinfection also increases. Important design parameters in the case of the hand pump cylinder are available flow area, which is a function of the lift, and head diameter of the check valve. Characteristics of the valve, i.e., lift and head diameter and corresponding flow area, are given in **Table 7**.

Inlet velocity of water for all geometries was kept constant at 1.4 m/s. No practical flow was observed in the case of 10% flow area opening. The rate constants obtained for 100%, 70%, and 40% flow area opening were estimated to be 0.020/s, 0.023/s, and 0.033/s, respectively. More than 80% reduction in the CFU/mL was observed in a single pass of water through the hand pump at 40% lift level of the valve (M. Badve & A.B. Pandit, unpublished data).

Further work on this modified pump combined with an arsenic removal filter was carried out at the Institute of Chemical Technology, Mumbai, India. A specifically designed filter was created by loading adsorbents such as 100 gm of iron-coated sand, 20 gm of activated charcoal, and 20 gm of activated earth in a glass column. Arsenic-contaminated water (100 ppm), when allowed to flow through the column at atmospheric pressure, underwent adsorption in the filter, resulting in almost 80% arsenic removal (M. Badve & A.B. Pandit, unpublished data).

SUMMARY POINTS

1. Clean drinking water, a basic human right, continues to be a challenge worldwide owing to the humongous and myriad physical, chemical, and biological pollutants in water bodies, thereby affecting human lives.
2. Ongoing, continuous, and commendable efforts by the United Nations, World Health Organization, and numerous stakeholders, including scientists, have resulted in marked improvement of the water scenario globally. However, much still must be done individually and collectively, especially for developing countries.

3. Conventional techniques, such as SODIS, filtration, hybrid filtration, and herbal water disinfection, are economical, easy to use, natural, and simple methods to obtain clean drinking water in developing countries, especially in the form of point of use in households for turbidity removal or pathogen inactivation. Techniques reviewed here have been compared (**Table 8**), and it appears that point-of-use methods such as the Tata Swach and Terafil are very promising. Water treatment at the community level needs more focus and development. Moreover, emerging techniques, such as herbal-based treatment, must be evaluated for cost effectiveness.
4. Harvested rainwater is an excellent source of clean drinking water that not only conserves water but also is amenable to simple and traditional disinfection techniques to render it pathogen free.
5. The quest for better technologies continues with the emergence of unique, efficient, and economical methods like plant materials, natural clays, herbs, hand pumps, and tippy taps to address the water needs of humankind.

FUTURE ISSUES

1. How do we address the demerits of SODIS, such as cloudy weather, geographical location, possible disinfection by-products, and leaching of plastic material from the bottles, bags, or metal and plastic pipes?
2. The simple, ubiquitous hand pump has not been systematically designed from the water quality perspective. Cavitation-based disinfection, the possibility of chemical dosing to take care of the residual contamination, flow rate, and the recommended pumping rates, among other factors, must be systematically studied to arrive at newer and more affordable hand pumps designs.
3. What are the quantitative cost analysis and large-scale feasibility of these techniques?
4. How do lethal pathogens like *Giardia* sp., *Legionella* sp., and *Cryptosporidium* sp. respond to individual water disinfection methods, and how can these be related with the local availability of these treatment materials?
5. Are disinfection by-products produced by the water disinfection methods (especially herbal and plant materials) described here, and how can we characterize them?
6. What is the potential toxicity of natural materials such as herbs used for water disinfection?
7. Is there a holistic approach to making simple water disinfection technologies more acceptable to rural populations, leading to affordable solutions and thus ensuring that existing and future generations are blessed with "the elixir of life?"

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